# REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188



| 1. REPORT DATE (DD-MM-YYYY) | 2. REPORT TYPE | 3. DATES COVERED (From - To) |
|---|---|---|
| 26-07-2015 | Final Report | 1-Jun-2011 - 31-May-2015 |

4. TITLE AND SUBTITLE
Final Report: Full-Wave Radio Characterization of Ionospheric Modification at HAARP

5a. CONTRACT NUMBER
W911NF-11-1-0217

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
206022

6. AUTHORS
Brett Isham

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Inter American University of Puerto Rico - I
P.O. Box 363255

San Juan, PR 00936 -3255

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
58966-EL-REP.9

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
We have studied electrostatic and electromagnetic turbulence stimulated by radiowave pumping and electron precipitation. We have made measurements of the spectra of those waves at megahertz frequencies, using ground-based radio receivers at HAARP in Alaska, and ground-based radio receivers, incoherent scatter radars, and in-situ measurements from Canadian, ESA, and Polish satellites at EISCAT in Norway.

15. SUBJECT TERMS
ionosphere, ionospheric modification, high frequency, radio, full wave, plasma waves, plasma instabilites, remote sensing, electromagnetic emissions, antenna, radio imaging, descending layer

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 15. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | Brett Isham |
| UU | UU | UU | UU | | 19b. TELEPHONE NUMBER 787-685-5223 |

**Report Title**

Final Report: Full-Wave Radio Characterization of Ionospheric Modification at HAARP


**ABSTRACT**

We have studied electrostatic and electromagnetic turbulence stimulated by radiowave pumping and electron precipitation. We have made measurements of the spectra of those waves at megahertz frequencies, using ground-based radio receivers at HAARP in Alaska, and ground-based radio receivers, incoherent scatter radars, and in-situ measurements from Canadian, ESA, and Polish satellites at EISCAT in Norway.


---

## Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

### (a) Papers published in peer-reviewed journals (N/A for none)

| Received | | Paper |
|---|---|---|
| 03/10/2013 | 1.00 | B. Isham, M. T. Rietveld, P. Guio, F. R. E. Forme, T. Grydeland, E. Mjølhus. Cavitating Langmuir Turbulence in the Terrestrial Aurora, Physical Review Letters, (03 2012): 105003. doi: 10.1103/PhysRevLett.108.105003 |
| 03/10/2013 | 2.00 | R.Yu. Yurik, E.D. Tereshchenko, M.T. Rietveld, B. Isham, V. Belyey. The spatial features of the up- and downshifted maxima in stimulated electromagnetic emissions, Advances in Space Research, (05 2012): 619. doi: 10.1016/j.asr.2012.05.013 |
| 07/26/2015 | 8.00 | W. A. Scales,, P. A. Bernhardt,, B. Isham,, E. Kendall,, S. J. Briczinski,, N. E. B. Fuentes,, O. Vega-Cancel. Electron gyro-harmonic effects on ionospheric stimulated Brillouin scatter, Geophysical Research Letters, (08 2014): 5710. doi: |
| 09/17/2013 | 4.00 | E. Sergeev, S. Grach, A. Shindin, E. Mishin, P. Bernhardt, S. Briczinski, B. Isham, M. Broughton, J. LaBelle, B. Watkins. Artificial Ionospheric Layers during Pump Frequency Stepping Near the 4th Gyroharmonic at HAARP, Physical Review Letters, (02 2013): 65002. doi: 10.1103/PhysRevLett.110.065002 |
| 09/17/2013 | 5.00 | A. Mahmoudian, W. A. Scales, P. A. Bernhardt, A. Samimi, E. Kendall, J. M. Ruohoniemi, B. Isham, O. Vega-Cancel, M. Bordikar. Ion gyro-harmonic structuring in the stimulated radiation spectrum and optical emissions during electron gyro-harmonic heating, Journal of Geophysical Research, (03 2013): 1270. doi: 10.1002/jgra.50167 |
| **TOTAL:** | | **5** |

**Number of Papers published in peer-reviewed journals:**

## (b) Papers published in non-peer-reviewed journals (N/A for none)

| Received | | Paper |
|---|---|---|
| 03/10/2013 | 3.00 | Brett Isham. Waves of Progress, INTERNATIONAL Innovation, (11 2011): 29. doi: |
| **TOTAL:** | | **1** |

**Number of Papers published in non peer-reviewed journals:**

---

## (c) Presentations

1
Radio diagnostics for the Puerto Rico CubeSat.
Brett Isham, Jan Bergman, Fredrik Bruhn, Amilcar Rincon-Charris, Pedro Capo-Lugo.
Measurement Techniques in Solar and Space Physics.
Boulder, Colorado, USA, 20-24 April 2015.

2
Stories from the past year and what they say about the future.
Brett Isham.
A Workshop to Consider the Future of Radio and Space Physics.
Ithaca, New York, USA, 30 March - 1 April 2015.
Invited.

3
A project for the new Arecibo Observatory heating facility: The Aguadilla radio array.
Brett Isham.
Leibniz Institute of Atmospheric Physics.
Kuhlungsborn, Germany, 15 January 2015.
Invited.

4
Observations and modeling of narrowband electromagnetic emissions at HAARP and EISCAT.
Wayne Scales, Alireza Mahmoudian, Haiyang Fu, Maitrayee R. Bordikar, Alireza Samimi, Paul A. Bernhardt, Stanley J. Briczinski Jr., Mike J. Kosch, Andrew Senior, and Brett Isham.
American Geophysical Union Fall Meeting.
San Francisco, California, USA, 15-19 December 2014.

5
Plans for an MF/HF radio imaging array in Aguadilla, Puerto Rico.
Brett Isham.
Conference on Remote Radio Sounding of the Ionosphere.
Tromso, Norway, 12-14 November 2014.
Invited.

6
The Arecibo Observatory: history, engineering, and science.
Brett Isham.
Conference on Remote Radio Sounding of the Ionosphere.
Tromso, Norway, 12-14 November 2014.
Invited.

7
Radio diagnostics and analysis on the Puerto Rico CubeSat.
Jan Bergman, Fredrik Bruhn, Brett Isham, Amilcar Rincon-Charris, Pedro Capo-Lugo.
European Planetary Science Congress.
Cascais, Portugal, 7-12 September 2014.

**Number of Presentations:** 7.00

## Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | | Paper |
|---|---|---|
| 08/31/2014 | 6.00 | Paul A. Bernhardt, Louis J. Lanzerotti, Herbert C. Carlson, Anthea J. Coster, John C. Foster, Sixto A. Gonzalez, David L. Hysell, Brett Isham, Elizabeth A. Kendall, Kristina A. Lynch, Konstantinos Papadopoulos. Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/Thermospheric Research: Report of a Workshop, Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/Thermospheric Research. 20-MAY-13, . : , |
| **TOTAL:** | **1** | |

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | Paper |
|---|---|
| **TOTAL:** | |

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## (d) Manuscripts

| Received | | Paper |
|---|---|---|
| 08/31/2014 | 7.00 | A. Mahmoudian, W. A. Scales, P. A. Bernhardt, B. Isham, S. J. Briczinski, E. Kendall, N. E. B. Fuentes, O. Vega-Cancel. Electron gyro-harmonic effects on Ionospheric Stimulated Brillouin Scatter, Geophysical Research Letters (05 2014) |
| **TOTAL:** | **1** | |

**Number of Manuscripts:**

## Books

Received Book

**TOTAL:**

Received Book Chapter

**TOTAL:**

## Patents Submitted

## Patents Awarded

## Awards

The PI is an invited member of the scientific organizing committee for the 2016 COSPAR (Committee on Space Research, part of the International Council for Science) General Assembly, 30 July - 7 August 2016, session C5.1D4.1, on Active Space Experiments.

The PI was an invited speaker at two conferences and one institute seminar, and participated in preparing an invited talk for a third conference:

Stories from the past year and what they say about the future.
Brett Isham.
A Workshop to Consider the Future of Radio and Space Physics.
Ithaca, New York, USA, 30 March - 1 April 2015.
Invited.

Plans for an MF/HF radio imaging array in Aguadilla, Puerto Rico.
Brett Isham.
Conference on Remote Radio Sounding of the Ionosphere.
Tromso, Norway, 12-14 November 2014.
Invited.

A project for the new Arecibo Observatory heating facility: The Aguadilla radio array.
Brett Isham.
Leibniz Institute of Atmospheric Physics.
Kuhlungsborn, Germany, 15 January 2015.
Invited.

Radar sounding of the auroral plasma.
Cesar La Hoz, with contributions from Brett Isham.
41st European Physical Society Conference. Berlin, Germany, 23-27 June 2014.
Invited.

## Graduate Students

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
|---|---|---|
| Brett Isham | 0.40 | |
| **FTE Equivalent:** | **0.40** | |
| **Total Number:** | **1** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Gaith Mohammad | 0.00 | computer science |
| Hector Ortiz-Colon | 0.00 | computer science |
| **FTE Equivalent:** | **0.00** | |
| **Total Number:** | **2** | |

## Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

## Names of Personnel receiving masters degrees

| NAME |
|---|
| **Total Number:** |

## Names of personnel receiving PHDs

| NAME |
|---|
| **Total Number:** |

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Sub Contractors (DD882)

## Inventions (DD882)

# Scientific Progress

Advanced digital radio receiving systems have been used with the DoD HAARP high-power high-frequency (HF) radio transmitter in Alaska to measure the electromagnetic field of stimulated radio emissions from the ionosphere. During the period of transition of HAARP management from DoD to the University of Alaska, complementary observations were performed at the EISCAT Observatory in Norway, using the EISCAT high-power HF transmitter and during natural energetic events.

The work falls into the general area of ionospheric remote sensing, focusing especially on the development of new radio techniques. The ionosphere, which starts at about 90 km, is part of the Earth's high-altitude atmosphere. The ionosphere contains free electrons and can reflect, deflect, and scatter radio waves, and can support electrical currents, plasma turbulence, and radio emissions. These radio emissions and turbulence may be driven by natural energetic particles, and can also be stimulated using high-power, high-frequency (HF) radiowave pumping (or heating).

In order to study this turbulence we use radio receivers to observe stimulated radio (electromagnetic) waves and powerful radars to observe enhanced ion and electron (electrostatic) waves. Collaborators measure optical emissions driven by energetic electrons accelerated by turbulent processes.

Radio systems measure the directionality of stimulated radio emissions versus frequency as a function of angle within and across the magnetic meridian plane, the polarization state of radio emissions from turbulence, and the growth and decay of the emissions at sub-millisecond time resolution.

Properties of ionospheric plasma irregularities and turbulence that have been studied through single and multiple-point radio measurements performed as a part of this project include the polarizations and spatial locations associated with specific spectral features of the radio emissions, the creation and evolution of artificial descending plasma layers created during very high-power radiowave transmissions, and the creation and development of the turbulence on short and long time scales.

In August 2012 data were recorded at HAARP in joint experiments at HAARP with colleagues from Virginia Tech and the Naval Research Laboratory, including students from Interamerican and Virginia Tech. Several new experiments were performed involving the descending layers and polarization of the pump and stimulated radio waves (O, X, and Z mode waves).

In November and December 2014 data were recorded at the EISCAT observatory in Norway. Measurements were made of both natural and artificial enhancements.

As a direct result of this work, artificially-excited Langmuir turbulence has been shown by the PI to occur naturally in the ionosphere. Naturally-occurring turbulence is directly related to artificially-excited turbulence. Langmuir turbulence is a specific type artificial turbulence known to occur in controlled laboratory and space plasma experiments and thought to occur in other space and astrophysical plasmas, including the terrestrial magnetosphere, planetary foreshocks, the interplanetary medium, the solar corona, and pulsar magnetospheres.

The demonstration by the PI, during the course of this project work, that Langmuir turbulence occurs naturally in the ionosphere is the first proof of Langmuir turbulence occurring naturally in space plasmas.

In its most developed form, Langmuir turbulence contains electron Langmuir modes trapped in dynamic density depressions known as cavitons. Cavitons have been shown to be artificially produced in the Earth's ionosphere during high-power radiowave pumping experiments as deduced from radar spectra.

The earth's ionosphere is now the first space plasma for which conclusive evidence exists of natural cavitation, as a result of this project.

A topic for future study is the relationship between natural energetic radio events events and naturally-occurring plasma turbulence. Energetic radio events events are well-known to be related to plasma turbulence created by high-power artificial radio transmissions. Natural radio emissions are also known to occur, and, when natural cavitating turbulence was identified, we began work on attempting to determine whether or not a direct relationship between natural plasma turbulence and natural radio emissions exists. It is hoped that this can will be completed during the course of future work.

In the longer term we would like to apply our new receiver and antenna designs to identifying not only the time and frequency of the emissions but also their location via radio interferometry and imaging. Measurements by the PI and collaborators have allowed determination of the azimuth and elevation angles of the source regions by the phase difference method, which is related to the methods we have been developing for imaging. Results to date show that different parts of the stimulated radio emission spectrum are generated in different regions of the ionosphere, possibly in an elongated region along the geomagnetic field.

This has implications not only for the radio technology involved but also the application of knowledge of plasmas in space, for both unmanned and manned missions, and for industrial processes and energy production on earth.

The work carried out for this project will directly impact the development of radio systems for observations at HAARP and related facilities including the EISCAT Observatory in Norway and the Arecibo Observatory in Puerto Rico. These include the possibility of oblique-angle, full-polarization, direction-of-arrival, and radio imaging measurements.

As a result of knowledge gained during the course of this work, we are planning to install radio receivers at the Interamerican University campus in Aguadilla, Puerto Rico. Along with receivers at the Interamerican Bayamon campus, the Aguadilla receivers will observe radio emissions created by the Arecibo high-power HF transmitter and also serve as a bistatic receiving site for the VIPIR radar located at the USGS observatory in Cayey, Puerto Rico, which is operated by NOAA and the University of Colorado.

In addition, we plan to use the phase-coherent capability of the receivers to develop a radio imaging capability. With sufficient resolution the large scale distribution of striations within the HF pump beam will be measurable.

The measurements at HAARP and EISCAT supported by this project have laid the groundwork for future work at HAARP, EISCAT, and with the new high-power HF transmitter which recently saw first light at the Arecibo Observatory in Puerto Rico.

During the course of this work the PI has been an invited speaker at a number of scientific meetings (listed in this and past project reports). During the course of this work the PI served as an invited member of the National Research Council committee on the role of high-power, high frequency transmitters in advancing ionospheric research. The committee wrote a report, which has now been published by the National Research Council and which contributed to the successful transition of the HAARP observatory in Alaska from DoD to the University of Alaska. The PI is currently serving as an invited member of the scientific organizing committee for the session on active space experiments at the 2016 COSPAR General Assembly, scheduled for 30 July to 7 August 2016. COSPAR is an abbreviation for the Committee on Space Research, and is a part of the International Council for Science, a multinational scientific organization sometimes described as the United Nations of science.

## Technology Transfer

Interaction with private companies Trigon Digital Inc., based in Quebradillas, Puerto Rico, Scion Associates, in Port Townsend, Washington, and Bruhnspace AB, in Uppsala, Sweden. Joint work includes enhancement of company expertise in digital receiver systems and antenna technology.